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A Study of Power Diode Failure Mechanisms in the U.S. Army Research Laboratory 30-mm Solid Propellant Electrothermal-Chemical (SPETC) Gun Facility

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13. ABSTRACT *(Maximum 200 words)*

Experiments have been performed with a 100-kJ Pulse Forming Network (PFN) at the U.S. Army Research Laboratory (ARL) for the purpose of characterizing semiconductor diodes which serve as capacitor-protecting crowbar devices. These devices are viewed as critical electronic power components required for electric gun research that is currently in progress within the U.S. Army and elsewhere. As part of this study, computer techniques were used to refine and develop the understanding of the dynamic, or switching, behavior of PFN diodes. In combination with experimental results, the computer simulations helped to define particular conditions within a given electric gun system that can cause vulnerable or stressful situations for the semiconductor devices under test. It was determined from analyses of the various data collected, that when operated in a PFN under specific loading conditions (simulated here with fixed resistive loads), diodes are subject to transient or high frequency voltage peaks. In some experimental cases at the ARL, the magnitude of the rate of change in voltage (dV/dt) across the devices was such that catastrophic failure was observed. The details of the boundary conditions necessary for device failure are described and several solutions that will circumvent operational problems including device grouping, choice of diode reverse recovery time, and selection of capacitive and inductive circuit parameters are discussed in detail. Background information describing some fundamental physics of semiconductor diodes and their role in electrothermal-chemical (ETC) propulsion technology is provided first.

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TABLE OF CONTENTS

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LIST OF FIGURES

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1. INTRODUCTION

It is of critical importance to offer voltage reversal protection in pulsed power systems since most energy storage capacitors are sensitive to, and can be damaged by, swinging or oscillating voltages (Sarjeant 1990). Semiconductor diodes are used in pulsed power systems as shunt rectifying devices that protect energy storage capacitors from voltage reversals. The presence of silicon diodes has a strong effect on the pulse-shaping characteristics of a given power system, and, in some cases, they can contribute toward an overall increased electrical efficiency of the system. Diodes are successfully used as pulse power components in several facilities currently involved in electric gun research at the U.S. Army Research Laboratory (ARL) and in several other research organizations (Grater 1994; Hammon, Bhasavanich, and Warren 1991; Oberle and Wren 1994; Rhinehart, McGowan, and Singh 1990; Weise et al. 1993; White et al. 1994; Wofford, Baker, and Day 1991). The end result is a decrease in operational lifetime for capacitors that are allowed to oscillate in a pulse forming network (PFN). Since they are basically used as a shorting path across the capacitors during a voltage reversal, semiconductor diodes are usually referred to as "crowbar" diodes, where they clamp or "crowbar" the capacitors for the duration of a reversal cycle.

It should be noted that other techniques have been developed that can effectively produce the same crowbarring action without the direct use of solid-state devices (Merger et al. 1990). Some of these systems take advantage of high current ignition switches, liquid mercury devices that require considerable volume within the power system. There is also additional control circuitry needed for proper timing of an ignition switch that can be made exterior to the PFN.

Hence, there is an obvious attraction to a self-reliant, solid-state switch that requires minimal volume and hardware for the PFN designer. The bad news is that semiconductor devices are destroyed when too much current (heat) is allowed to penetrate their junction. Damage occurs as a result of excessive junction temperature caused by ohmic heating, which leads to increased device conductivity; this results in additional current flow and further temperature increases. The conductivity is directly proportional to the concentration of mobile current carries in the device, and is itself a function of operating temperature. The relationships between conductivity (σ_i) and mobile carrier concentration (n_i), and carrier concentration and temperature are given, respectively, in equations 1 and 2.

$$\sigma_i = q(\mu_n + \mu_p)n_i \tag{1}$$

$$n_i(T) = 3.88 \times 10^{16}\, T^{3/2} \exp(-7000/T) \text{ cm}^{-3} \text{ (for silicon above 50 K)} \tag{2}$$

where, q represents the charge on an electron and μ_n and μ_p are the electron and hole mobilities.

As the energy of the valence electrons is increased due to the additional thermal energy, more electrons are excited to the conduction band of the material, which result in a structure that conducts current more freely (Tyagi 1991). If the material is not allowed to dissipate the additional heat quickly enough, this process will continue until the melting point of the device is reached and ultimately destroyed. This condition is often referred to as "thermal runaway."

• Diode Reverse Recovery Time (t_{rr}). For pulsed power applications where switching is utilized, as in electric gun systems, the t_{rr} of the semiconductor diode is an important parameter for consideration. The t_{rr} is that time required for the diode to switch from an "on" or conducting state to "off" or high impedance state. This parameter is a function of two quantities, namely, junction capacitance (C_j) and the minority carrier lifetime (t_p) of the semiconductor device (for long base diodes) or the transit time of the minority carriers (short base diodes). A diode is considered short base when the diode's neutral base width (W_n) is less then the diffusion length (L). The frequency response of the overall electrical network is directly limited by the t_{rr} of the device in which it operates. So, for fast switching applications, it is a requirement that the recovery time be kept as small as possible (Sze 1985).

The t_{rr} consists of the time associated with the minority carrier concentration at the depletion edge (t_s) and a "fall" time component (t_f) due to capacitive storage of minority carriers throughout the depletion region. This is expressed in equation 3 and illustrated by Figure 1.

$$t_{rr} = t_s + t_f \tag{3}$$

For long base diodes, where the neutral region is large, t_s is effectively the minority carrier lifetime (t_p) for the bulk material. The minority carrier lifetime is a result of three electron-hole recombination processes. These are direct band-to-band (radiative) recombination, indirect recombination due to carrier traps in the energy band gap (Schockley, Hall, Read or SHR recombination) and a three particle process known as Auger recombination. In general, the minority carrier lifetime can be increased by increasing the carrier traps or defects in the semiconductor crystal (this is accomplished through a process known as

electron bombardment), but the tradeoff is an increase in the reverse saturation current (current flow in reverse bias mode) of the device (Tyagi 1991). This is seen as a practical disadvantage with regards to PFN operation since energy storage capacitors will discharge faster having diodes of higher reverse saturation current. A typical reverse recovery current waveform for a *pn* junction diode is shown in Figure 1.

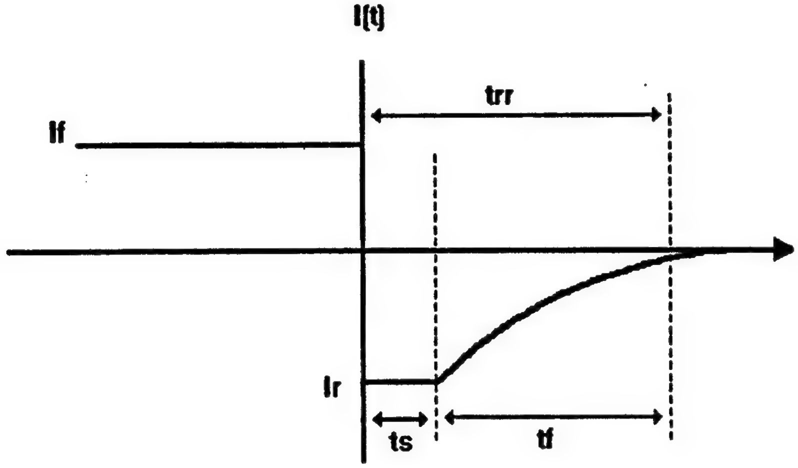

Figure 1. Typical reverse recovery behavior of a diode.

In some instances, the transit time of the carriers is smaller then the carrier lifetime. This is true for "short base" diodes that have a narrow base width and are much faster in terms of recovery time. For this case, the current due to the diffusion of carries in a sample of material (either electrons or holes) is given by

$$I = q\, D\, dP_o/dx\, A_j \tag{4}$$

or, alternatively, for a short base diode,

$$I = (q\, D\, P_o\, A_j) / W_n \tag{5}$$

where

q = electronic charge = 1.602×10^{-19} C
D = diffusion coefficient of material (cm^2/s)
P_o = excess carrier concentration (cm^{-3})
A_j = junction area of the device (cm^2)
W_n= width of the device neutral region (cm)

Given that the minority carrier charge, which must be removed during this "fall" time, is

$$Q = A_j \, q \, P_o \, W_n/2, \tag{6}$$

and the current expressed as a function of the charge due to minority carriers with respect to time is

$$I = Q/t, \tag{7}$$

then the result of replacing the expression for current in equation 7 with that from equation 5, combining with equation 6 and solving for time, gives

$$t = t_s = Q/I = (A_j \, q \, P_o \, W_n/2 \,) \, / \, (q \, D \, P_o \, A_j \, / \, W_n) \tag{8}$$

$$t_s = 1/2 \, (W_n^2/D), \tag{9}$$

where t_s is referred to as the transit time of the device. It is interesting to note that the value of t_s can be made smaller then the carrier lifetime of the bulk material with obvious adjustments in the base width and diffusion coefficient. For example, for short base diodes, it is generally required that the base width be on the order of the diffusion length (L), which is the square root of the diffusion coefficient (D) multiplied by the carrier lifetime (t_p). Assuming that the base width in equation 9 is equal to the diffusion length, the resulting transit time through the base is twice as fast as that of the carrier lifetime. This represents a substantial improvement in device speed. The diffusion coefficient is a function of carrier mobility, a basic property of semiconductors, and it is desirable to have a large mobility material (such as GaAs) as necessary to obtain a fast device; and, as just demonstrated, narrow base width diodes are preferred due to their improved recovery time. So, with respect to high-speed devices, the semiconductor

material type and diode geometry are of significant importance and should not be overlooked. It should be stressed that the tradeoff in using a fast recovery device is that of lower breakdown voltage. This results from the smaller available depletion width, which effectively lowers the voltage capability of the device and forces the use of multiple diodes in series. This is a situation that tends to be bulky and expensive, as will be discussed later in this report.

If the diode's t_{rr} are incompatible with the requirements or capabilities of a PFN, it is possible for electrical breakdown to occur in the semiconductor junction (Katulka et al. 1991). It should be noted that the capabilities of an electric gun PFN are variable, by design, such that the diode t_{rr} may be shorter than required for one set of boundary conditions and marginal or even inadequate (as will be shown later in the report) for others. It is recommended that care be exercised when selecting semiconductor diodes for pulsed power applications of this nature. Figure 2 shows how the thickness of diode junction depletion region varies with applied voltage. The depletion region with (W), as seen in Figure 2, is given by the following relation.

$$W = [(2\varepsilon_s/q)\{(1/N_a) + (1/N_d)\}\{V\}]1/2 \tag{10}$$

where,

ε_s = semiconductor permitivity (F/cm)
q = electronic charge (C)
N_a = acceptor impurity concentration (cm-3)
N_d = donor impurity concentration (cm-3)
V = junction voltage (reverse bias).

As indicated by equation 10, when a reverse bias is increased across the junction, the depletion region widens and the resulting maximum or critical electric field in the depletion region becomes larger. This enables the diode to have a relatively large value of reverse blocking voltage (typically several kilovolts for power diodes) and a relatively small forward voltage limit (usually a few volts). The amount of time required for the diode to switch between the forward and the reverse modes is dependent upon the time for the depletion region to reach its maximum width and is governed by the reverse recovery characteristics of the device, as discussed previously. Once again, if a voltage of appreciable magnitude is applied across the device junction faster than what is required for W to achieve a thickness wide enough

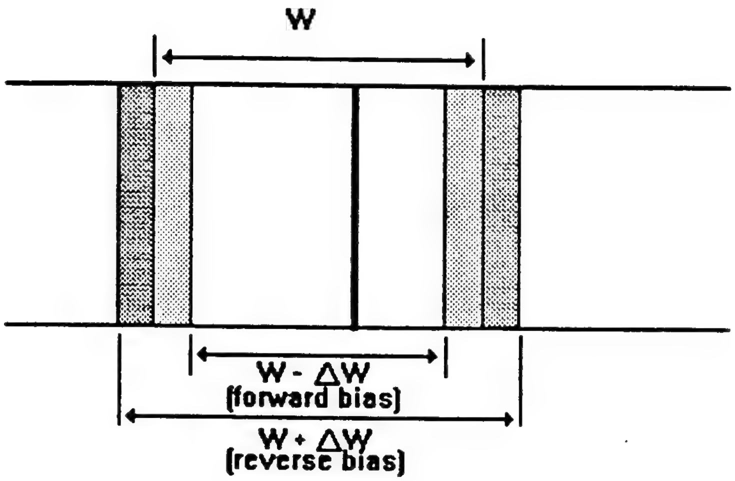

Figure 2. Variation of depletion region thickness with applied bias.

to avoid electrical breakdown, then the diode can be destroyed from internal breakdown through the junction.

The focus of this report deals with experiments and theoretical calculations that have been performed and analyzed at the ARL on a 100-kJ pulsed power supply used for electrothermal-chemical (ETC) gun research. The main area addressed is in characterizing the crowbar diodes' performance when exposed to high-voltage switching transients produced by the discharging of the PFN. This work was initiated in response to a series of electric gun firings in the 30-mm ETC gun facility, when several occurrences of diode failures (catastrophic in some cases) were encountered. The approach taken was to perform discharge experiments at low energy levels (to avoid further damage to the PFN) with fixed resistive loads while examining the current and voltage characteristics of the diodes. This was coupled with computer calculations of the PFN to further study the diodes. After validating the computer code by direct comparisons with experimental data, further calculations were performed to demonstrate the dependence of the rate of change in voltage (dV/dt) with respect to the PFN switch closure times, circuit capacitances, and series inductance in the diode conduction path.

The result of this work led to a better understanding of the physical processes involved in the pulsed power system relevant to crowbar diode operation, which are viewed as a critical power component for several types of electric gun research programs.

2. EXPERIMENTAL APPROACH

A schematic diagram of the PFN under consideration is given in Figure 3. In this case, the PFN consists of five triggerable submodules of capacitor banks that can be independently discharged through the ignition closing switches. This feature provides a level of flexibility to the electric gun researcher in that it allows the capability of multiple pulsed power profiles to the electric gun system (Katulka et al. 1991). The diode failure problems experienced during laboratory electric gun firings were found to occur in only the first submodule of the PFN; thus, indicating a nonuniform or unique pattern of power dissipation to the first submodule diodes. Semiconductor failure was observed for several gun firings and also in fixed load discharges using a 100-mΩ load resistance. This occurred at relatively high initial PFN energies on the order of 50 kJ for each discharge. As a result, efforts were focused on studying the current and voltage characteristics of this submodule's diode, at a reduced system energy, in comparison to the other diodes in the system. This work was performed with fixed-resistive load discharges and verified using computer techniques.

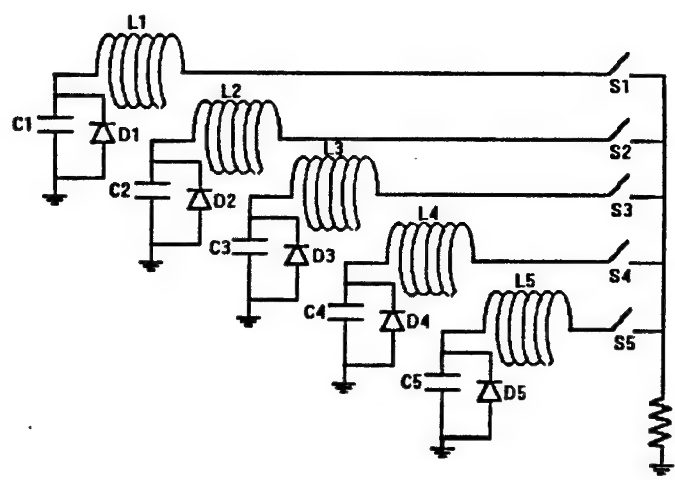

Figure 3. Circuit diagram for 100-kJ PFN used for electric gun applications.

Experiments were performed with PFN discharges into 35-, 100- and 200-mΩ load resistors. It was determined from experimental measurements of diode current and voltage that only for the case of the 100-mΩ load did a large dI/dt and dV/dt occur across the diode terminals in the first submodule. Experimental current and voltage waveforms as measured for this case are given in Figures 4 and 5 and

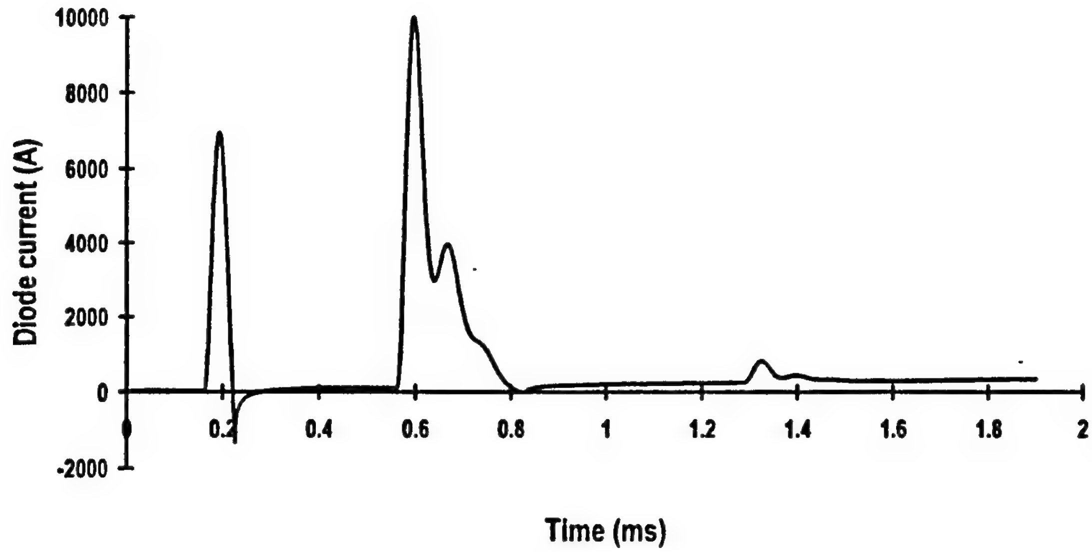

Figure 4. Diode current measurements for 100-mΩ load.

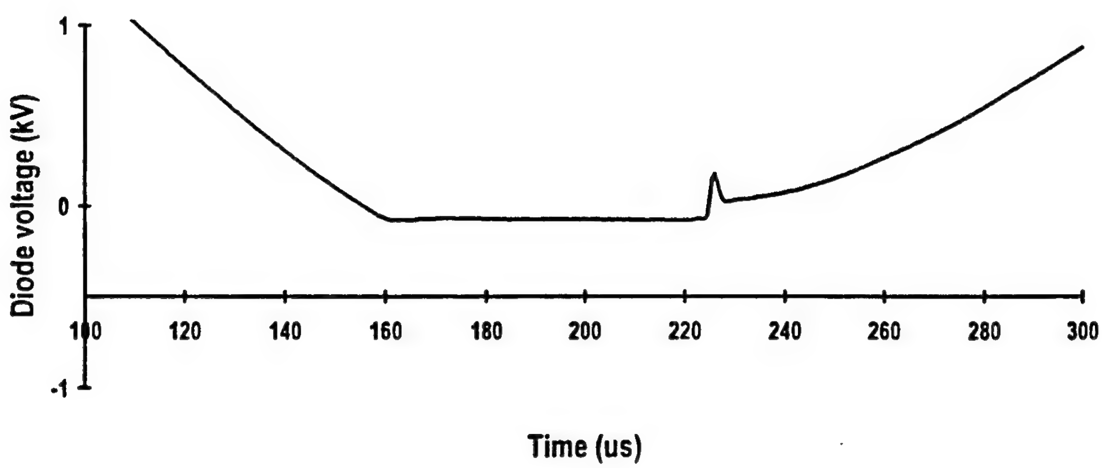

Figure 5. Diode voltage measurement with 100-mΩ load.

the transient waveforms can be seen at 226 µs in time. These results were corroborated later with computer calculations, and it was also demonstrated that a large dV/dt (see Figure 6 at 280 µs) was experienced on the first submodule diode with a current-depended plasma load computer simulation. The plasma load generally varies from 30 mΩ to hundreds of milliohms during the plasma functioning and the simulation results are given in Figure 6. The computer simulation shows that although the rate of change in current is smaller for the plasma case, the overall current magnitude is larger than the resistive

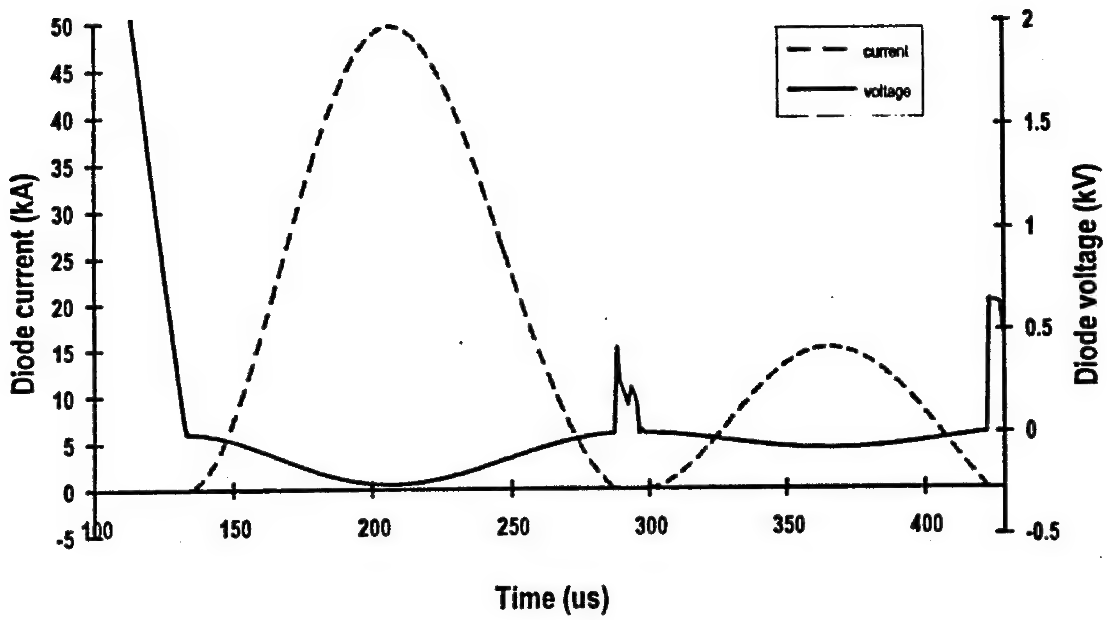

Figure 6. Computer simulation of current-dependent plasma load.

load case, indicating a greater impedance mismatch situation, and a large dV/dt is still evident. The large dV/dt is a possible cause of why diode failure was observed in some experimental gun firings where plasma loads are used. It is noted that for the 100-mΩ load case, the current waveform exhibits a small pulse of current over a 50-μs period followed by a second pulse starting just before the 600-μs point. However, it was of further interest to discover that the rate at which the current decreased through the device was extremely large. In one experiment, the maximum rate of change (dI/dt) for the decreasing current is calculated at 124.6 A/μs, which is the largest dI/dt for the three test cases considered here and the largest dI/dt for any of the five submodules of the PFN.

This is pointed out since large dI/dt's can lead to overheating in semiconductors (as discussed earlier in the report) and they are also indicative of other potential problems such as large dV/dt's. It is estimated that the t_{rr} of these diodes is on the order of 50 μs, which when subject to the dI/dt of the 100-kJ PFN, will result in application of reverse voltage on a diode still in the forward biased mode (Rinaldi 1994). In other words, the diode cannot turn off as fast as the application of reverse voltage across its terminals occurs, and the result is an excessive reverse voltage applied to the diode terminals. In fact, direct measurements of the voltage across the diode junction (Figure 5) provide definite evidence that a fast pulse

of reverse voltage occurs across the diode as it is switching from the forward to reverse mode. It should be pointed out that this transient voltage occurs in spite of the fact that the diodes are placed directly in parallel with the 400-μf energy storage capacitors. As seen in Figure 5, a rapidly rising voltage is applied to the diode as current conductions ceases at approximately 226 μs in time. The dV/dt for this particular case is calculated at 127 V/μs. Here it is proposed that the diode's depletion region is still quite narrow, as it should be in forward bias when the PFN exerts a rapid reverse voltage across the junction ultimately causing voltage breakdown of the device. This will be true in general when the voltage capability of a forward biased diode, which is typically in the range of several volts, is reached and exceeded.

From additional studies, it was determined that the relationship between the magnitude of the dV/dt across the diode was a linear function with respect to the overall voltage (energy) of the PFN. This relationship was established by performing experiments with larger overall energy levels while continuing to measure diode voltages. The results of these experiments are shown in Figure 7. The data of Figure 7 can be used to evaluate the expected dV/dt for a given system voltage level and it is then possible to determine the safe operating area for these particular diodes with respect to maximum dV/dt. For instance, it was noted that during several high energy experiments where the system voltage was at 7-kV, and using the 100-mΩ load, diode failures were experienced repeatedly. This voltage level corresponds to the 300-V/μs point on the curve in Figure 7. Once the characteristics of maximum dV/dt and t_{rr} of the crowbar diode are established, it becomes imperative that the PFN is of a design that will not exceed these parameters. A straightforward design method to be used to determine an adequate PFN configuration is through the use of a circuit analysis computer code that can characterize dynamic diode behavior. This approach has been taken on the PFN of Figure 3 and is discussed in the following section.

• <u>Circuit Parameter Effects</u>. The dependence of the switching transient applied to the diode in the first submodule, and other submodules, with respect to PFN closing switch times, submodule capacitance, and series inductance were studied further with a basic electronic circuit analysis code (Microcap III). It was determined that in the presently configured PFN (Figure 3), the relatively small value of submodule capacitance in the first bank, 400 μf, coupled with the other submodules discharging relatively quickly after the first, ultimately caused the rapid decrease in diode current of the first submodule. This resulted in a large dI/dt and subsequent large dV/dt once diode conduction ceased. The submodules 1 through 5 begin discharging at 0, 40, 80, 120, and 180 μs, respectively. The combination of the 400-μf capacitance with the submodule inductance and series resistance produce an effective capacitor discharge time of 165 μs. When the diode stops conducting current, the series inductance in the buswork surrounding the

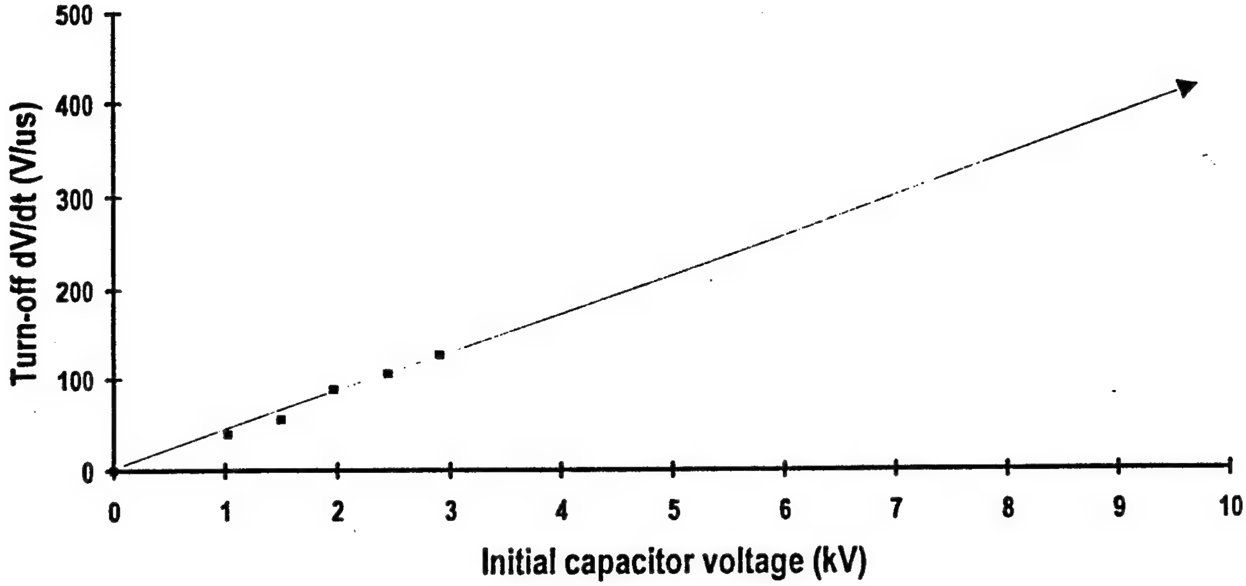

Figure 7. Rate of change in diode voltage (dV/dt) vs. PFN system voltage.

diode immediately produces a transient voltage (dV/dt) that is responsible for diode destruction as described in the previous section. The results of these calculations are given in the plot of current and voltage in Figure 6, where an initial voltage of 10-kV (maximum system voltage) is assumed for the PFN. The calculations reliably predict the transient voltage waveform—specifically the dV/dt across the diode terminals at approximately 226 μs into the discharge cycle. It was determined from other computer calculations that the effect of the submodules beginning discharge at 80, 120 and 180 μs are responsible for the abrupt current turn off, and also magnitude of dV/dt, on the first submodule's diode. That is, as the current is exponentially decaying in the diode, the final three submodules are switched into the network and substantially increase the voltage across the load. This forces an increased dI/dt through the inductor and diode of the first submodule that drives the current to zero (Katulka et al. 1991). The realization of this condition brings about one solution to the dV/dt problem as expanding the overall pulse width by discharging the last three submodules after the completion of the initial submodules diode conduction.

A computer calculation with this modification is given in Figure 8, where two submodules are fired 400 μs after the initial submodule. In general, to completely avoid an increased diode dI/dt of any submodule, no subsequent submodule should be discharging while a preceding submodule diode is conducting. The main difficulty here is that the system is now limited as to the length of the power pulse

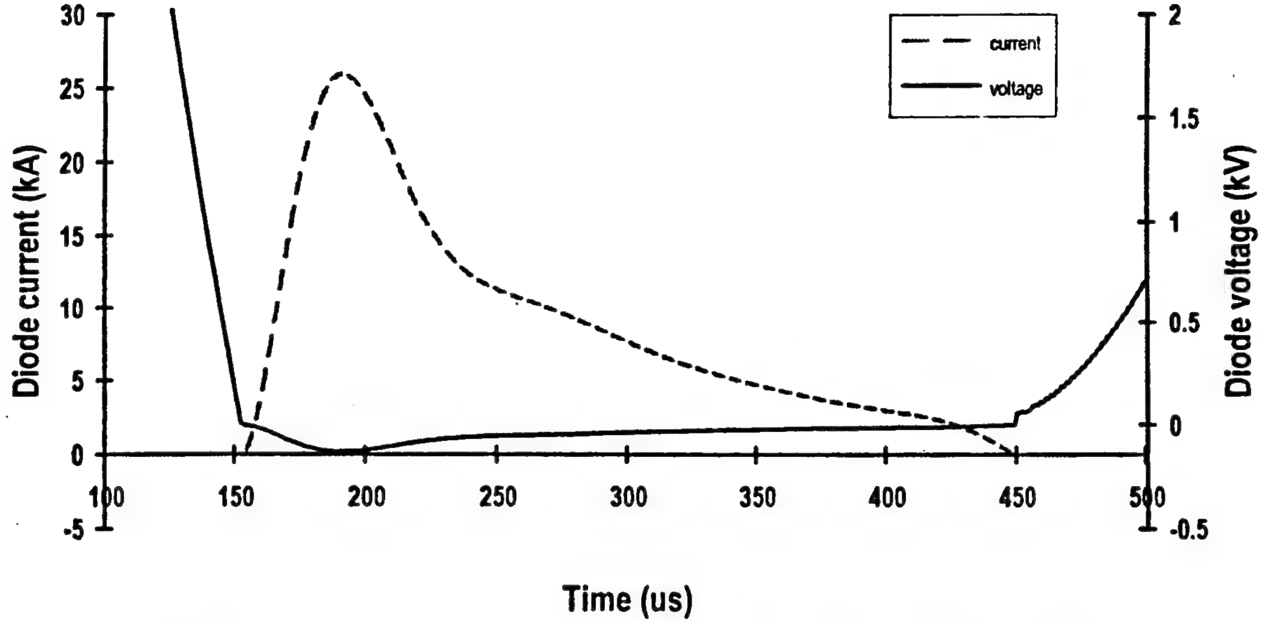

Figure 8. Current and voltage of first submodule diode in delayed discharge.

width that can be produced by the PFN. This is an extremely confining solution to the dV/dt problem in terms of pulse power flexibility and is not a very attractive solution if pulse shaping is a necessity.

Further calculations were performed with the PFN discharges in which the total capacitance in the first submodule was varied in an effort to minimize the magnitude of the diode dV/dt. These results are shown in Figures 9 and 10 where the capacitance of the first submodule is increased from 400 µf in Figure 6 (the standard used in the PFN), to 800 µf in Figure 9, and 1,600 µf in Figure 10. It is noticed that the increase in capacitance is quite effective in eliminating the dV/dt on the diode. The problem with this approach is that the total energy of the first submodule is now increased by a factor of 4, the PFN output power by about 30%, and the total pulse width of the first submodule is now twice as large as in the initial case. This solution may not be problematic if the pulse width and other complications can be tolerated, and if the voltage on the first submodule can be reduced to deal with the added capacitive energy and power from the first submodule.

The final area of investigation was in the study of the effects of the series inductance of the first submodule diode conduction path. The results of computer calculations where this inductance was varied from 1.8 µH to 0.4 µH are given in Figure 11. It becomes clear that minimal inductance, experimentally realized by keeping buswork lengths to a minimum, will have a very large impact on the reduction of the diode dV/dt. This approach may be difficult to implement in practice, but is extremely attractive since

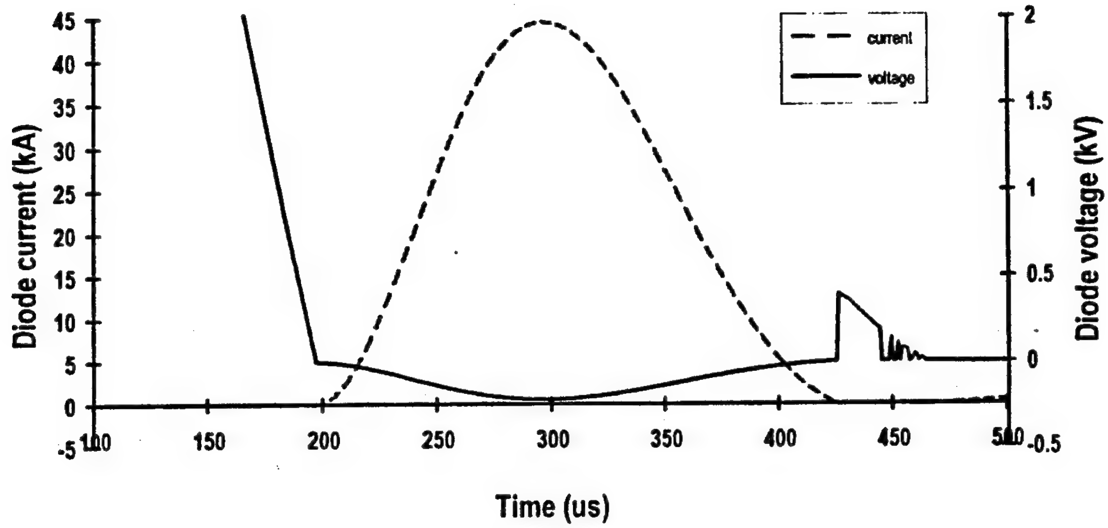

Figure 9. Current and voltage of first submodule with 800-µf capacitance.

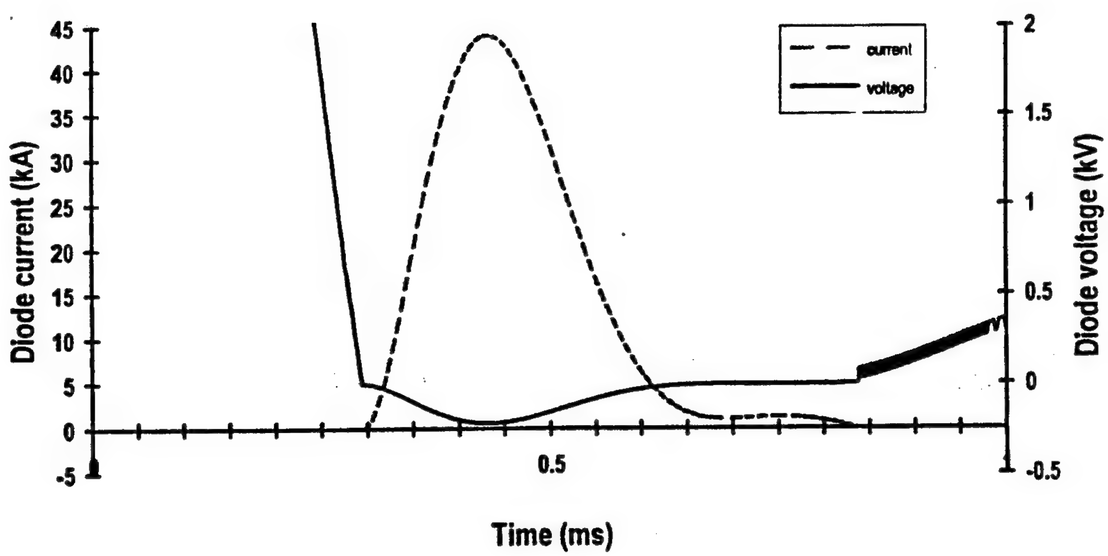

Figure 10. Current and voltage of first submodule with 1600-µf capacitance.

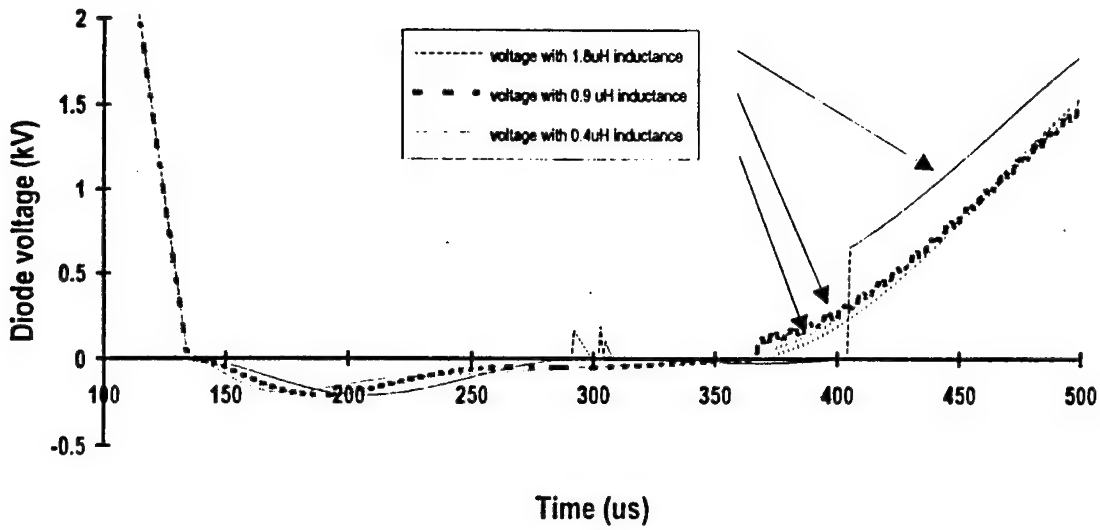

Figure 11. Effect of varied inductances in the diode path.

any series inductance in the diode path is not necessary for proper PFN operation and will primarily serve to introduce rapidly changing voltages as demonstrated by the experimental measurements and calculations shown here.

3. SUMMARY AND CONCLUSIONS

It has been shown through a variety of experimental measurements and computer calculations that the crowbar diodes of a PFN currently used for electric gun applications are subject to rapidly changing voltage signals (dV/dt's) that resulted in catastrophic diode failures in experiments involving both plasma and resistive loads. It was determined that when crowbar diodes are protected by PFN capacitors, unwanted series inductances can still produce rapidly changing voltage signals that can exceed the t_{rr} and voltage limits (dV/dt) of the semiconductor devices. An identifiable solution to overcome the dV/dt problem is to use only fast recovery diodes that are capable of tolerating fast reverse voltages offered by the discharging PFN. Short base diodes having high carrier mobilites will offer faster turn off times and should be considered for switching applications as encountered for electric gun research. This approach will likely increase the size, volume, and cost of the overall PFN since faster diodes tend to have decreased voltage capabilities, will require more devices in series, and are generally more expensive than slower-acting devices. Alternatively, the PFN pulse width can be increased such that only subsequent

submodules are discharged only after diode conduction has ceased in the preceding submodules. This will also impose limits on the minimum pulse width obtainable for a given PFN.

It has been demonstrated that further protection of diodes from dV/dt's is possible through an increase in the capacitance surrounding each crowbar diode. This is considered a practical solution to the dV/dt problem as long as the capacitance used for protection is within the limits of system energy, power, and pulse width constraints.

Also, it was illustrated that by reducing series inductances in diode paths, a direct reduction in the ability of the discharge circuit to produce unwanted transient voltages across diode junctions will result. It may be best to consider as many approaches as possible and apply the benefits of each of the techniques that have been considered here in terms of realizing a PFN that is capable of producing a variety of pulse shapes, one that has a high electrical efficiency, remains robust, compact, and is also practical to construct.

Finally, it should be stressed that the use of computer techniques and calculations can provide an effective method of clarifying or characterizing the dynamic behavior of pulsed power systems as necessary to establish safe operating regions for associated pulsed power hardware. By adopting such techniques, situations that exceed the threshold of properly operating devices can be identified and avoided, and the time and effort of designing and analyzing pulsed power systems will be spent more efficiently.

4. FUTURE WORK

It became apparent as the work detailed here progressed that the semiconductor diode requirements used for this application of PFN's involve specialized semiconductor devices. Many of the power rectifiers available and in use today are geared more toward lower frequency applications as opposed to pulsed power as in electric gun research. This is not to say that these devices cannot be adapted to perform reliably in all pulsed power systems. However, as previously illustrated in this report, the unique application of diodes in electric gun power supplies, that rely on multiple stages and switching of network elements, do require devices with large current capabilities, high voltage ratings, and adequate recovery times. The general trend for fast recovery diodes is in the direction of lower voltage blocking limits, which is in conflict with the high voltage requirements found in systems of this nature. As a result,

potential areas for further work exist in terms of providing the optimal semiconductor device, and this may include the usage of new high-speed materials or novel semiconductor diode geometries.

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